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TITLE: LABORATORY STUDIES OF COAL DRYING, PYROLYSIS
AND COMBUSTION FOR UCC

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ABSTRACT

Experimental and theoretical analyses show that uncontrolled water invasion during underground coal conversion (UCC) is harmful at all stages of UCC. By contrast, if water invasion is prevented, coal porosity can be created for further processing, pyrolysis can yield uniform hydrocarbon products, gasification can produce a uniform product, coal is fully consumed (not bypassed) during combustion, and environmental problems are minimized.

INTRODUCTION

The Four Corners Region of New Mexico has long served as the major source of fossil fuel for the 10% (and growing) of the U.S. population which lives in the American Southwest. Over the long term, assuming continued rejection of the nuclear option, despite a temporary supply of Alaskan oil, and including possible future contributions from the Kaiparowits Region of Utah, this fuel source must continue to supply electricity and hydrocarbon fuels for the Southwest. Other regions of the United States, as well, may need hydrocarbons from this Region. However, with the depletion of oil and natural gas supplies, it will be necessary to turn to coal both for electric power and for the hydrocarbon fuels.

Although the coal reserves of the Four Corners and Kaiparowits Regions are vast, the strippable coal is far more limited—underground mining is already proposed for the Kaiparowits Region, and the 3° dip of the Four Corners coal seams leaves only relatively small amounts of coal at stripping depth, i.e., less than about 65 m (200 ft). Economic factors thus require that deeper coal be recovered, and safety and environmental factors demand development of new methods to recover that coal. The LASL concept of underground coal conversion (UCC) is one promising new method.

In its complete form (simpler versions are also envisioned, as will be discussed), the LASL advanced concept for subbituminous coals in arid or semi-arid regions involves preliminary physical isolation of the coal from the surrounding aquifers, followed by four chemical steps: (1) The coal is dried at about 120°C to produce greater porosity, to create uniform and

reproducible conditions for subsequent processing, to accomplish the drying with low-grade heat, and to recover valuable water. (2) The coal is pyrolyzed at about 300–600°C to recover gaseous and perhaps liquid hydrocarbons. Some hydrocarbons will be sold as fuels or petrochemical feedstocks. Part may be blended with the coal gasification products so that a material of very uniform quality can be supplied. (3) The coal is gasified with O_2/CO_2 feed to yield an intermediate-Btu fuel. (4) The fuel gas is cleaned and blended. LASL sees the use of this gas at a mine-mouth electricity generation station, but other uses for the fuel can be envisioned.

Because the Navajo Nation is equivocal in its attitude toward recovery of its strippable coal, the long-term fuel supply for present and future Four Corners Region electric generators is uncertain. Other coal supplies must be sought. Conventional underground mining is one expansive possibility. However, chemical recovery of deeper coal by the LASL concept should be reasonably straightforward, if water isolation (as in the previous paragraph) could be accomplished. Once water influx is controlled, successive drying, pyrolysis, then gasification with oxygen/carbon dioxide mixtures would provide a uniform, intermediate-Btu fuel gas with relatively low sulfur content to mix with and augment the powdered coal being burned in the generators. Because of the existing stack-gas cleaning facilities, and because the boilers handle coal pyrolysis gases, such generating stations offer a particularly advantageous site for a staged development of various concepts ultimately to go into UCC technology for more broad-scale use.

In considering any coal recovery scheme for arid regions, one must recognize the overriding importance of water conservation.

THEORY

It is, perhaps, obvious that coal cannot burn if it is too wet. Control of water influx into coal beds during underground coal gasification (UCC) has seldom been attempted, and underground processing yields have been degraded accordingly. Uncontrolled water influx has implications throughout both the combined steps of simple gasification (UCC) and the individual steps of LASL's UCC.

Water Influx - The current practice in UCC has been to create a gas bubble in the processing region of the coal bed by excessive gas pressure in a way to impede water influx. This technique has been tried during both the Hanna and the Hoe Creek experiments.¹⁻⁴ Although initially this approach seemed successful it is now apparent that over-pressurization bubbles are not the long-term answer for either UCC or UCC water control: First, a gas bubble underground is inherently unstable and will tend to move or flatten, second, with different-sized cracks, gas will preferentially escape in the larger cracks while the pressure is still too low to move water out of other smaller cracks; third, the very fact of pressurizing the system will increase pore pressure and increase water influx. These inherent problems cause engineering, economic, and environmental difficulties.

Eastern European work⁵⁻⁸ has included pumping to eliminate water, but there is little evidence that such pumping has been carried out in ways which produce a major sealing of the water channels in the coal. Moreover, a continuous flow control is more necessary, perhaps, than is the initial moisture control.

The initial approach to water control being pursued under the LASL concept is to select coal beds which are relatively dry and have low seam permeability to exclude water flow. This requirement, along with many others, has led LASL to the arid Four Corners Region. Although dry coals are an important initial consideration, successful processing will require that the water flow be limited or excluded. Special techniques will be necessary to achieve this water control.

Water, Carbon Dioxide, and Drying - Permeability experiments with subbituminous coals from the Fruitland Seam have shown that permeability, when these coals are recompressed to realistic *in situ* stresses, is so low (about 0.05 millidarcy, $0.05 \mu\text{m}^2$) that drying does not occur at a reasonable rate, except under forced convective transport. When dried, permeability increases to a large enough value (about 8 millidarcy, $8 \mu\text{m}^2$) so that auxiliary openings are no longer important in the total gas flow.⁹ This permeability for dry, compressed San Juan coal is a little lower than for some other dried coals,¹⁰ but certainly most low-rank coals will show adequate permeability for UCC after moisture removal.

During drying of coal under static conditions, heat must flow inward through regions of porous, dry coal. Since coal demonstrates low thermal conductivity and large amounts of heat must flow in to evaporate moisture which is still in the wet regions inside the pieces of coal, the process cannot be accelerated much. Overheating the outer surfaces of the coal results¹¹ in much of the heat being removed by steam moving counter-current to the heat flow of the vaporization process. Also, coal pyrolysis limits the temperatures which can satisfactorily be used for solely coal drying.

To facilitate heat transfer, carbon dioxide gas with a low viscosity and a high heat capacity, leads to a rapid convective drying. In addition, the carbon dioxide adsorbs strongly to coal surfaces and displaces moisture.

If the coal is not thoroughly dried prior to gasification, then processing gases isolate and bypass coal regions as the flame front traverses the coal bed. This bypassing occurs for three reasons: First, the flow of the reactant gases will tend to follow natural cracks in the coal because of the very low permeability

of the undried coal. (Dried coal, as already mentioned, has a high enough permeability to permit porous flow.) Second, as just discussed, the high heat capacity of wet coal, the poor heat transfer, and the countercurrent cooling of the dried coal by moisture evaporation slow the heating of moist coal. This prolonged cooling will prevent some sections of the coal zone from reaching temperatures hot enough to cause pyrolysis--instead, the hot (dry) regions will get hotter and react faster while the wet coal regions stay wet, cold, and unreacted. Third, small amounts of water vapor condensing on cooler portions of the coal bed, can block off further gas flow and coal reaction. We feel that this condensation is a major reason for bypassing underground processing.

Water and Pyrolysis - Earlier work¹² has shown that pyrolysis of San Juan Mine coals is a process which is almost thermally neutral--pyrolysis proceeds rapidly without generating or consuming large amounts of heat as the temperature moves through the range 300°-600°C. On the other hand, if liquid water invades a region of pyrolyzing coal, the effect can be disastrous to the pyrolysis both because water vaporization consumes large amounts of heat and because water transport (liquid and gaseous) dominates heat transfer.

As a specific example of the effects of water invasion, consider water injection into char at 300°C. The heat capacities of the water and of the char are such that the energy necessary to heat 1 g of water from 25° to 100°C and boil it (615 cal, 2.57 kJ) are more than enough to cool 10 g of char from 300° to 100° C. Once a char region has cooled to 100°C, moisture is not evaporated, and any additional condensation of liquid water will physically block the gas flow patterns at the wet regions.

Pyrolysis creates even more porosity and a lower flow impedance in Fruitland coals than exists in the dried coal. Pyrolysis will generate gases with heating values, in the neighborhood of 500-600 Btu/SCF (19-22 MJ/m³ at 15.56°C and 0.1016 MPa).

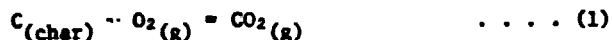
The importance of pyrolysis to fuel recovery in UCC has been emphasized by Derman and Nikolaeva.¹³

Water and Gasification - The gasification of coal char with air or oxygen to low- or intermediate-Btu fuel gases (about 100-300 Btu/SCF, 4-11 MJ/m³) occurs only at high temperatures, both for kinetic and for thermodynamic reasons.

Four char (represented as carbon) reactions are of critical importance to the fuel-production reactions of UCC and UCC. These reactions are listed below, along with accepted¹⁴ values for the standard heats of reaction at 25°C (298K) and 927°C (1200K) and the standard free energies at 427°C (700K) and 927°C (1200K) for these reactions. Also $\Sigma(H_{1200}-H_{298})$ is listed, showing the heat absorbed in raising the system to the reactant temperatures of 1200K. All thermodynamic values apply for g-moles of the reactions written.

Reaction 1 delivers heat, but the CO₂ product is not a fuel gas--fuel gases result only from Reactions 2-4, and, as discussed earlier, from pyrolysis reactions. However, Reaction 1 is kinetically important because it can be initiated at relatively low temperatures (some chars ignite in air at temperatures around 250°C) and because the heat of reaction can produce temperatures which permit rapid progress of Reactions 2-4. Invasion of liquid water retards Reaction 1 both

by blocking out gaseous reactants and by cooling the char below its ignition temperature.



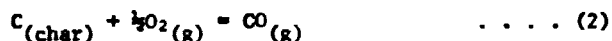
$$\Delta H^\circ_{298} = -94.1 \text{ kcal} = -394 \text{ kJ}$$

$$\Delta H^\circ_{1200} = -94.4 \text{ kcal} = -395 \text{ kJ}$$

$$\Delta F^\circ_{700} = -94.5 \text{ kcal} = -395 \text{ kJ}$$

$$\Delta F^\circ_{1200} = -94.7 \text{ kcal} = -396 \text{ kJ}$$

$$\Sigma(H_{1200} - H_{298}) = 11.0 \text{ kcal} = 46 \text{ kJ}$$



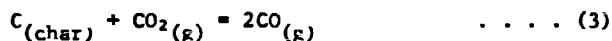
$$\Delta H^\circ_{298} = -26.4 \text{ kcal} = -111 \text{ kJ}$$

$$\Delta H^\circ_{1200} = -27.1 \text{ kcal} = -113 \text{ kJ}$$

$$\Delta F^\circ_{700} = -41.5 \text{ kcal} = -174 \text{ kJ}$$

$$\Delta F^\circ_{1200} = -52.0 \text{ kcal} = -218 \text{ kJ}$$

$$\Sigma(H_{1200} - H_{298}) = 7.4 \text{ kcal} = 31 \text{ kJ}$$



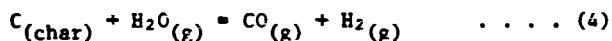
$$\Delta H^\circ_{298} = +41.2 \text{ kcal} = +172 \text{ kJ}$$

$$\Delta H^\circ_{1200} = +40.3 \text{ kcal} = +169 \text{ kJ}$$

$$\Delta F^\circ_{700} = +11.6 \text{ kcal} = +48 \text{ kJ}$$

$$\Delta F^\circ_{1200} = -9.4 \text{ kcal} = -39 \text{ kJ}$$

$$\Sigma(H_{1200} - H_{298}) = 14.5 \text{ kcal} = 61 \text{ kJ}$$



$$\Delta H^\circ_{298} = +31.4 \text{ kcal} = +131 \text{ kJ}$$

$$\Delta H^\circ_{1200} = +32.5 \text{ kcal} = +136 \text{ kJ}$$

$$\Delta F^\circ_{700} = +8.4 \text{ kcal} = +35 \text{ kJ}$$

$$\Delta F^\circ_{1200} = -8.7 \text{ kcal} = -36 \text{ kJ}$$

$$\Sigma(H_{1200} - H_{298}) = 12.1 \text{ kcal} = 51 \text{ kJ}$$

For a temperature of 1200K, Reaction 1 will deliver 94.1 kcal per g-mole of carbon consumed, but part of this heat reflects energy which had to be supplied for the necessary high reaction temperature. For an oxygen burn, 11.0 kcal is needed, 3.9 kcal to heat the carbon to 1200K, and 7.1 kcal to heat the oxygen. For an air burn, an additional 13.4 kcal is needed to heat the inert nitrogen.

(To be precise, these thermodynamic values apply for idealized pressures, i.e., fugacities, of 1 atm, or 0.1013 MPa, for both oxygen and nitrogen. However, this idealization has no significant effect upon the following discussion.)

Reaction 2 delivers both heat (27.1 kcal per g-mole) and a fuel gas (CO). The kinetic limitations of this reaction require high temperatures and favorable reaction conditions, e.g., 1200K as was used for the calculations. There are also thermodynamic limitations, as will be discussed under Reaction 3.

For oxygen burns this 27.1 kcal is considerably larger than the energy, 7.4 kcal, needed to heat the reactants to 1200K, and this exothermic Reaction 2 should be balanced by an endothermic (heat-absorbing) reaction such as Reactions 3 and 4. With air burns, however, an exothermic-endothermic balance is less important because heating the air and char to 1200K absorbs 20.8 kcal of the 27.1 kcal evolved. As corollary, though, liquid water invasion into an air-burn-

ing coal bed can be particularly objectionable in cooling the reaction zone and thereby degrading the product. Oxygen systems are less sensitive to this effect since additional heat is available.

Reaction 3 absorbs heat (ΔH° is positive), and the reaction can be very useful in utilizing the evolved heat of Reaction 2 to produce more CO fuel gas. This reaction is extremely temperature sensitive, as is indicated by the free energies at 700K and at 1200K. At 1200K the value of ΔF° is negative, corresponding to a very large percentage (98%) of CO fuel in the gas which will form if oxygen is put into contact with char at that temperature. By contrast, at 700K the positive value of ΔF° corresponds to only 2% of CO fuel and the gas is no longer even combustible. There is no reason to propose that the reverse of reaction 3 will occur under reaction conditions listed here.

Reaction 3 is preferable to Reaction 4 in the arid Southwest because the latter reaction involves water. In many ways Reaction 3 and 4 are equivalent as far as endothermic-exothermic balance is concerned, and comparable product degradation occurs if the reaction temperature is dropped by a liquid water influx. However, injection of water into a UCG system may cause unnecessary bypassing and fuel wastage.

Water and Product Uniformity - Reaction 3 limits the Reaction 1 - Reaction 2 interrelationship. For temperatures below 600°C or for high gas velocities the CO formation faces kinetic limits which degrade the product below the thermodynamic predictions as just discussed. However, for reaction of porous, bulk char at high temperatures (850°C and higher) and at gas flow velocities suitable for UCC, the thermodynamic limit as calculated from Reaction 3 will closely prevail and the kinetic degradation will not be important. At the high temperature thermodynamic limit, a highly uniform fuel product will result.

For moist, impermeable coal (as opposed to dry, porous char) the gas flow is largely through cracks. Here flow velocities can locally become very high, residence times can become very short, and pressures can vary throughout the reacting region. Under these conditions the kinetic limits will dominate even at high temperatures, and the system may not achieve the thermodynamic limit. In fact, the thermodynamic limit may shift to less favorable, high pressure conditions. The problem is further aggravated by local temperature variations associated with the erratic evolution of puffs of steam and pyrolysis products as the coal dries and pyrolyzes during combustion. All these factors will adversely influence product uniformity and quality during UCG with wet coal.

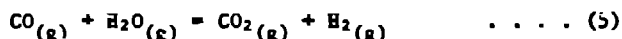
The thermodynamic limits, expressed in the heating value of the product gas which could, at equilibrium, be formed at various temperatures are shown in Fig. 1. For these cases, representing Reactions 3 and 4 (low heating value) with oxygen-burning or air-burning of the char, one can note a sharp drop in the heating value for temperatures below 800°C during formation. As cited above, the kinetic problems lead to further degradation of product quality.

Figure 1 indicates that there is no way that a product of adequate and uniform quality could be delivered if water is intermittently introduced into the gasification zone. Another point is that the thermodynamic maximum heating values for carbon monoxide/hydrogen product mixtures is approximately 300 Btu/SCF (11 MJ/m³) where oxygen has been used for the char

gasification; with air burns the values can only be just over 100 Btu/SCF (4 MJ/m³). Therefore, larger heating values than these indicate a contribution from pyrolysis gases. Pyrolysis is impossible to maintain in a coal bed for long processing periods. In fact, such time-dependent heating values with time have been noted in UCC experiments.

Finally, one must consider what happens to thermodynamic equilibrium as the gas product cools. Many years of commercial experience with the use of water gas show that the reverses of Reactions 3 and 4 usually do not occur as the CO cools. The explanation is that the formation of solid carbon in a cooling gas phase is kinetically difficult. Therefore, CO concentrations formed at equilibrium at high temperatures can be retained in nonequilibrium as the temperatures are lowered, even though a char/CO₂ mixture would be thermodynamically more stable. Particular catalytic conditions could alter this situation.

However, CO can often be destroyed at lower temperatures if water is present, through the shift reaction



$$\Delta F^\circ_{1200} = +739 \text{ kcal} = 3092 \text{ kJ}$$

$$\Delta F^\circ_{800} = -2297 \text{ kcal} = -9611 \text{ kJ}$$

Those free energies indicate that the reaction cannot produce CO₂ at high temperatures but can react almost completely to CO₂ at low temperatures. Furthermore, catalysts for the reaction exist in soil and ash.

This formation of noncombustible CO₂ from combustible CO is a further difficulty caused by uncontrolled water influx.

Water and Coal Bypassed in Combustion - Earlier comments have indicated that undried coal is more subject than char to incomplete combustion as the flame front moves through a coal bed. However, channel burning and bypassing of coal are so important that it is useful to recap the arguments in a special section.

Bypassing of coal is important economically (a) because it minimizes energy production from expensive drill holes and piping and (b) because it adversely affects the quality of the product fuel gas. Furthermore, as will be discussed, bypassing also leads to serious environmental problems.

In the LASL view the presence or influx of invading water is a major cause of erratic burning during UCC, leaving unburned coal behind. Here water blocks reactant gas flow through the bulk of the coal, thus also forcing flow into cracks. Such crack flow will require high local velocities to maintain overall flow, and the high velocities, in turn, will result in nonequilibrium. Water also delays heating coal to combustion temperatures, both by blocking heat flow and by consuming large amounts of heat. As a consequence, the hot regions expand while the cold regions react very little and fail to shrink.

If the coal is dried and is converted to char before combustion, channel flow is largely avoided, local flow velocities are low as compared to crack flow, reaction surfaces become very large, heating for gasification is simple, reactant gas concentration gradients across the burn front are reduced,

good utilization of the coal field is achieved, and product gas uniformity is maintained.

Water and Environmental Problems - Use of an unstable reaction bubble to control water influx, as discussed earlier, will sometimes lead to the escape of noxious gases as water plugs are pushed back in the cracks, thereby opening a path to the earth surface.

A well-burned, underground coal field would be expected to leave sulfur and trace elements tied up as harmless sulfates, silicates, etc. However, hot, unburned coal would generate hydrogen and other reducing gases by slow pyrolysis. These gases would release SO₂, H₂S, and trace elements which had once been trapped in the ash in an oxidized state. This condition has been noted in post-burn UCC measurements where residual high pressures of H₂S remain months after the burn.

Once pyrolyzed the char is not similarly reducing since low temperature oxidation of char produces CO₂, not CO, consistent with Reaction 3 which shows that CO₂ is preferred at low temperatures even if the oxygen supply is limited. Therefore, lingering residuals of char are environmentally much less objectionable than for unpyrolyzed coal.

Testing the Theory - A laboratory program was designed to test (where possible and deemed necessary) the feasibility of the steps of the LASL concept in UCC. After feasibility was established, later measurements would be made to provide the precise data needed for engineering design. Basically it was necessary to establish (a) that water influx could be controlled underground and (b) that the coal could be successfully dried, pyrolyzed, and gasified by processes which could be carried out underground.

Although we could see possible ways to control the water influx (e.g., by stress modification underground¹⁵), this problem is basically one which can only be proved by field tests. It is not answered in the present paper.

The question of drying, pyrolysis, and combustion, however, can be successfully represented in laboratory tests, as will be discussed.

EQUIPMENT - In some cases commercial drying ovens were used for heating the coal. However, most heating was done in specially designed, thick-walled, firebrick furnaces with electric heaters and temperature controllers.

For some measurements a balance supported a heavy-wire frame which entered a furnace through holes in the furnace bottom. The frame was used to support a coal block which could be weighed at will as it was drying or pyrolyzing.

Some coal blocks were wrapped in aluminum foil to control convection, but others were placed unwrapped into a furnace. Earlier work had also included forced convection.

Combustion was carried out in 100 mm quartz tubes in firebrick insulation. Ignition was by hot wires or by a torch heating the outside the quartz tube and air or oxygen was used for combustion. Coal or char was burned.

Cracks, pores, and shrinkage in dried and in pyrolyzed coal were examined by microscope. Weight changes were noted. Physical dimensions were measured. Cracking in temperature gradients was studied. Heat conduction was evaluated from drying rates. Earlier work had measured permeability.

Chemical analyses gave moistures volatiles, and ash.

Coal samples were recovered as quickly as feasible from the mine face, i.e., a day or two after blasting. Reasonably protected samples were dug from the rubble, and these samples were stored in double plastic bags. Coal was removed from the Fruitland Pit (Western Coal Co., Farmington, NM)

RESULTS

Chemical Properties - The Fruitland seam was found to have very nonuniform properties. Table 1 gives results from a single site but from different levels in the coal bed. This group of samples show moisture varying from 4.5% to 8.8%, and other specimens from the bed have shown as high as 11% moisture. Volatiles, too, are highly variable when measured after heating to 600°C in closed containers; this group varies from 22.1% to 45.6% volatiles. Ash varies from 6.4% to 41.8%.

Drying - Results of drying experiments on large blocks of mid-seam coal are given in Figs. 2 and 3.

Fig. 2 shows results for a 2 kg coal block in a furnace at 125°C (32°C above the Los Alamos boiling point). Loss of moisture was monitored by a balance mounted below the furnace. The gas was essentially still, and the coal was open to the air of the furnace. Drying was effectively complete in just over 1 day when 8.7% moisture had been removed.

Fig. 3 shows results for an 11 kg coal block sealed in aluminum foil and positioned in the furnace at 150°C. Here drying was extended to five days before 7.0% moisture had evaporated.

Table 2 indicates shrinkage on drying and cooling. As noted earlier, Table 1 lists further drying results.

Pyrolysis - Table 1 lists volatiles at 600°C, as mentioned earlier. Table 2 gives the shrinkage on pyrolysis and cooling along with the percent volatile at 600°C on a dry, ash-free basis.

A typical pyrolysis gas given off from Fruitland coal at 350°C has a heating value of about 500 Btu/SCF (19 MJ/m³) made up from 33 vol. % CO and H₂, 100 Btu/SCF; 29 vol. % C₁ to C₃ hydrocarbons, 400 Btu/SCF; 38 vol. % CO₂ and H₂O, 0 Btu/SCF.

Combustion - The Fruitland chars we studied in combustion experiments were produced in these laboratories. The chars were not totally pyrolyzed—pyrolysis continues up to about 900°C, and samples had not been at that elevated temperature. Samples, instead had been heated to various temperatures in the range 250°C (pyrolysis just started) to 500°C (a large fraction about 75%, of the hydrocarbons removed).

These chars sometimes ignited in air at temperatures in the range 275° - 325°C, and continued to burn after they had been removed from the furnace. Coal chunks wrapped in aluminum foil did not ignite on heating, but would ignite if removed and opened to the air.

Combustion of undried (but not moist) coal and of dry char (both - 1/4 in, - 1.3 cm) indicated significantly different behavior. Combustion was carried out at rates corresponding to consumption of 0.5 m of coal face per day in UCC or UCC. (This coal, however, was broken into small pieces.) The course of the combustion was examined periodically by removing insulating firebricks from the combustion tube.

The char initially ignited readily, and it reignited when air or oxygen flow was stopped and started. Char combustion moved smoothly, and a relatively flat burning face was maintained in all cases. The angle from vertical of the burn front changed with gas velocity — higher gas velocities produced larger, more horizontal burn fronts (lying elliptically in the circular tube), while slower burns gave smaller fronts which moved more vertical.

Coal was more difficult to ignite than char, and there was more tendency for air fires to extinguish spontaneously. Like char, coal tended to enlarge the burn front as velocities increased, and the burning faces again were essentially flat. At highest air velocities, channels started burning away from the flat burn front of more slowly burning coal.

There were also other differences in the burn fronts of the char and of the coal. Most notably coal combustion produced puffs from combustion of pyrolysis gases, and these puffs ignited running sparks on adjacent coal pieces. Then the sparks went out of their own accord only to ignite again later.

For char there was a very smooth region of burn, perhaps 1.5 cm thick, which was at about 1000°C (estimated from color). Flame propagation was through radiation and through the flow of hot gases. Unlike the coal case, there was no evidence of the puff-burning of char or of the running sparks associated with coal burning.

Fracture - With Fruitland coal we saw no evidence of the fracture associated with shrinkage upon water removal (as in the slacking of stored coal). However, the shrinkage shown in Table 2 for heating at 250°C would surely cause drying cracks in a coal bed.

Thermal fracturing offers a very important method of breaking up this coal. Thus a 20-kg chunk of coal can retain its shape and show little evident cracking as it dries. On the other hand, if this chunk of coal is removed from the furnace at 125°C and placed on a table at laboratory temperature, then this coal will develop cracks and in some cases will break into pieces 7-15 cm across.

INTERPRETATION OF DATA

The measured chemical properties show the Fruitland coal seam is highly variable in the vertical direction. Such variability emphasizes the importance of drying and pyrolysis to produce a uniform fuel gas. The pyrolysis products are economically significant¹⁶.

The drying experiments suggest that realistic sized coal blocks can be dried in times which are reasonable for UCC operations. Drying models have been offered.^{7, 18} Initially the flow of the heat-carrying gas would be through fabricated paths in the coal, but drying would produce increased permeability⁹ to permit efficient flow and more rapid drying. Tables 1 and 2 together show about 1% apparent volume decrease

for 7 wt % moisture removal; allowing for density differences between coal and water, this means about 10% of the bulk volume becomes pores and internal cracks.

The drying experiments (Fig. 1) can be evaluated to give the thermal conductivity of the dry coal. This value is low, $k = (91 \pm 6) (10^{-6}) \text{ cal/s}\cdot\text{cm}\cdot^\circ\text{C}$, or $(381 \pm 25) (10^{-6}) \text{ W/m}\cdot\text{K}$ and is only slightly larger than the conductivity of still air $79(10^{-6}) \text{ cal/s}\cdot\text{cm}\cdot^\circ\text{C}$. This low conductivity emphasizes the necessity of convective drying using CO_2 as a particularly useful agent.

The pyrolysis studies indicate that 350°C pyrolysis yields a product gas at 500 Btu/SCF. It could be blended with lower Btu fuel or be cleaned and shipped. With chemical shifting to remove CO and with H_2O and CO_2 removal, it would become an 800 Btu/SCF non-poisonous gas which could be blended into natural gas fuels. It could readily be upgraded to SNG (substitute natural gas) or other products if there were nearby plants already producing SNG. The yield of liquid plus gaseous pyrolysis products (Table 1) are economically important, as mentioned earlier. These hydrocarbons are valuable enough so that they should not be destroyed by underground combustion.

The combustion studies give evidence of erratic burning in wet coals. This phenomenon appears to be a precursor of the incomplete combustion of underground coal during UCC. (The problem presumably would have been worse with larger pieces of coal.) Because char contains no water, has more combustion surface than coal, and has adequate permeability to permit internal gas flow, it burns completely without such difficulty.

The easy ignition of char, and steady burning even with no external heat supply, suggest that there will be no problem in igniting dry char, even if it sits and cools underground before processing, as long as water is excluded.

The foregoing analysis of combustion finds support in earlier work¹⁹ which has emphasized the importance to combustion of coal drying, of coal particle size, and of air flow velocity in combustion engineering. Those authors point out that dry coal will burn with an efficiency approaching 84.1% while the same raw coal burns with maximum efficiency of 79.8%. Also they note that underfeed fires can be extinguished by too rapid air flow and that larger coal particles require lower air velocities for efficient combustion.

The fracturing of hot dry coal during cooling indicates that coal could be cracked underground even before pyrolysis — one would use pulsed heating, then cooling, to achieve both convection drying and cracking. Cracking on the large and small scale is achieved without temperature change during pyrolysis. And once a porous region has been produced, brisk and efficient processing is possible.

CONCLUSIONS

In all cases these results are supportive of the theory of underground coal processing presented under THEORY. We see no insurmountable technical problems existing for a staged underground coal conversion process, but we emphasize that all concepts in underground coal processing depend critically upon control of water influx. It is important that techniques for measuring and controlling, water flow be developed if this technology is to be a contribution in the Nation's energy supply.

NOMENCLATURE

ΔF° = standard free energy change at the Kelvin temperature indicated by the subscript for the reaction

ΔH° = standard enthalpy change at the Kelvin temperature indicated by the subscript for the reaction

$\Sigma(H_{1200} - H_{298})$ = standard enthalpy change for heating reactants

k = heat conductivity in the units listed

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Table 1 - Chemical properties of some Fruitland coal specimens from different levels at a single site.^a

<u>Seam Location</u>	<u>Moisture wt. %</u>	<u>600°C Volatiles wt. %</u>	<u>Ash wt. %</u>
Top	8.8	22.1	41.8
Middle	7.4	45.6	6.4
Bottom	4.5	35.6	15.9

^aSamples from San Juan Mine, Sage Pit, Western Coal Company. Seam 6 m deep; "top" sample 0.5 m from top of the seam; "middle" sample 2 m from bottom of the seam; "bottom" sample 0.5 m from bottom of the seam.

Table 2 - Dimensional changes induced in Fruitland coal by drying and pyrolysis.

Sample ^a	Temp. °C	Volatile ZDAF ^b	Δ decrease			Bulk
			<u>x-axis</u> ^c	<u>x-axis</u> ^d	<u>y-axis</u> ^d	
Top of seam	250		0	0	5.6	1.8
	400		2.8	1.1	4.7	2.4
	500		4.7	1.6	7.3	3.8
	600	44.7				
Middle of seam	250		0	0	1.1	1.0
	400		0	2.2	1.7	1.6
	500		0	4.5	7.2	3.2
	600	52.9				
Bottom of seam	250		0.3	1.2	1.2	0.8
	400		1.0	2.7	4.7	2.3
	500		1.7	2.7	3.2	2.4
	600	44.7				

^aThese are the samples described in Table 1.

^bDry, ash-free

^cPerpendicular to bedding planes.

^dAlong bedding planes; cleats not identified.

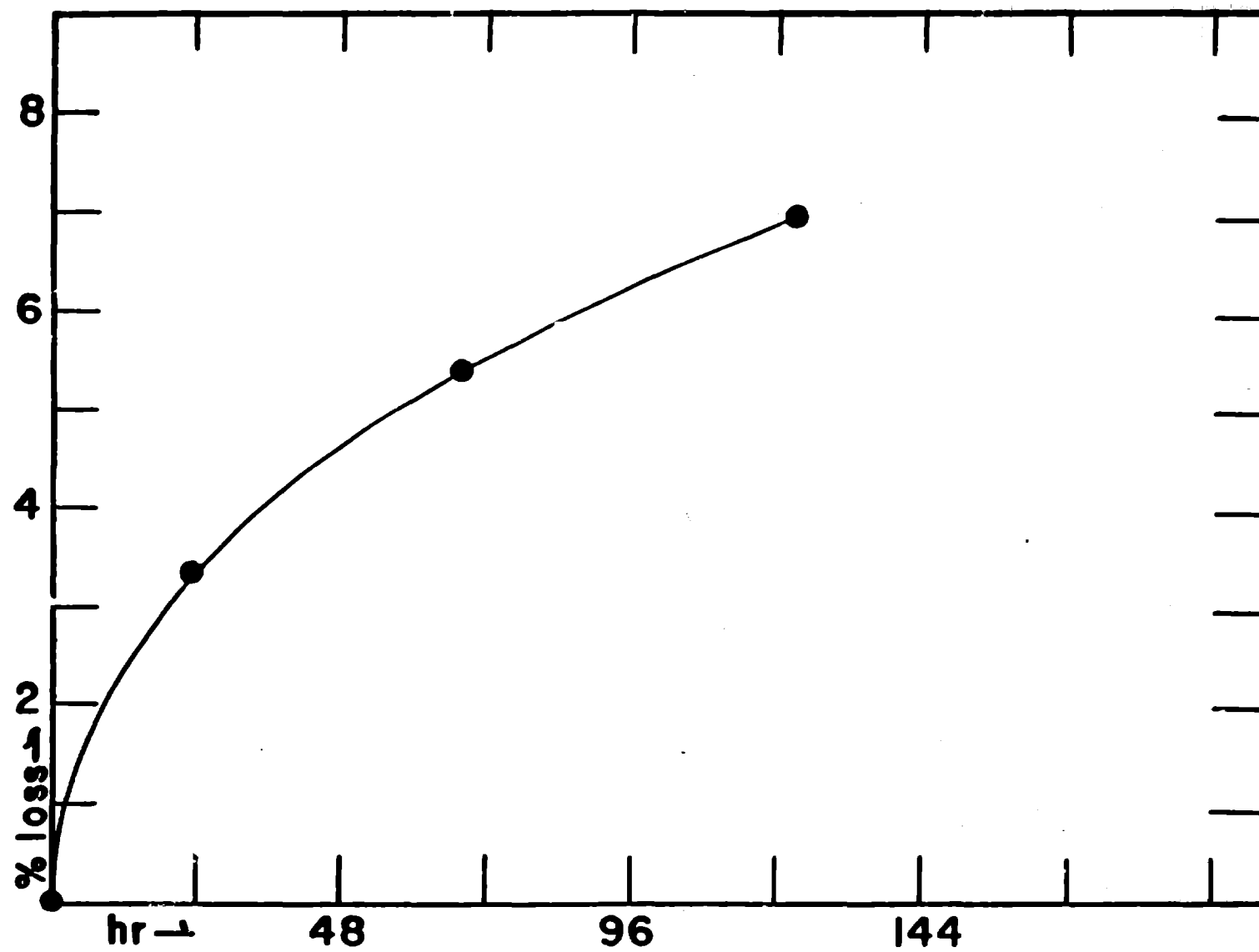


Fig. 3 - Drying of 11 kg piece of Fruitland coal at 57°C
above local water boiling point.

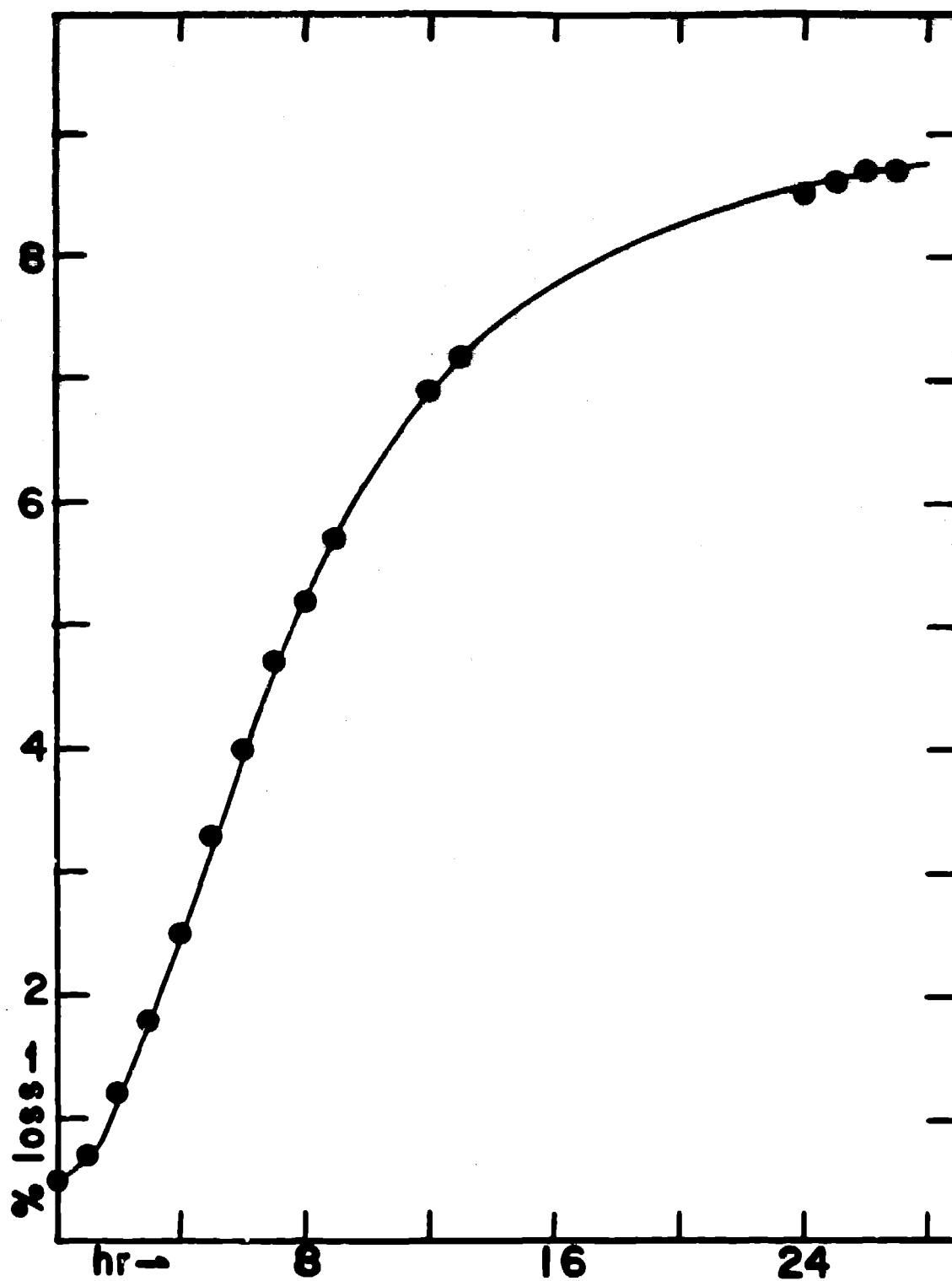


Fig. 2 - Drying of 2 kg piece of Fruitland coal at 32°C above local water boiling point. (Original 0.5% from air-drying in breeze for 3 days.)

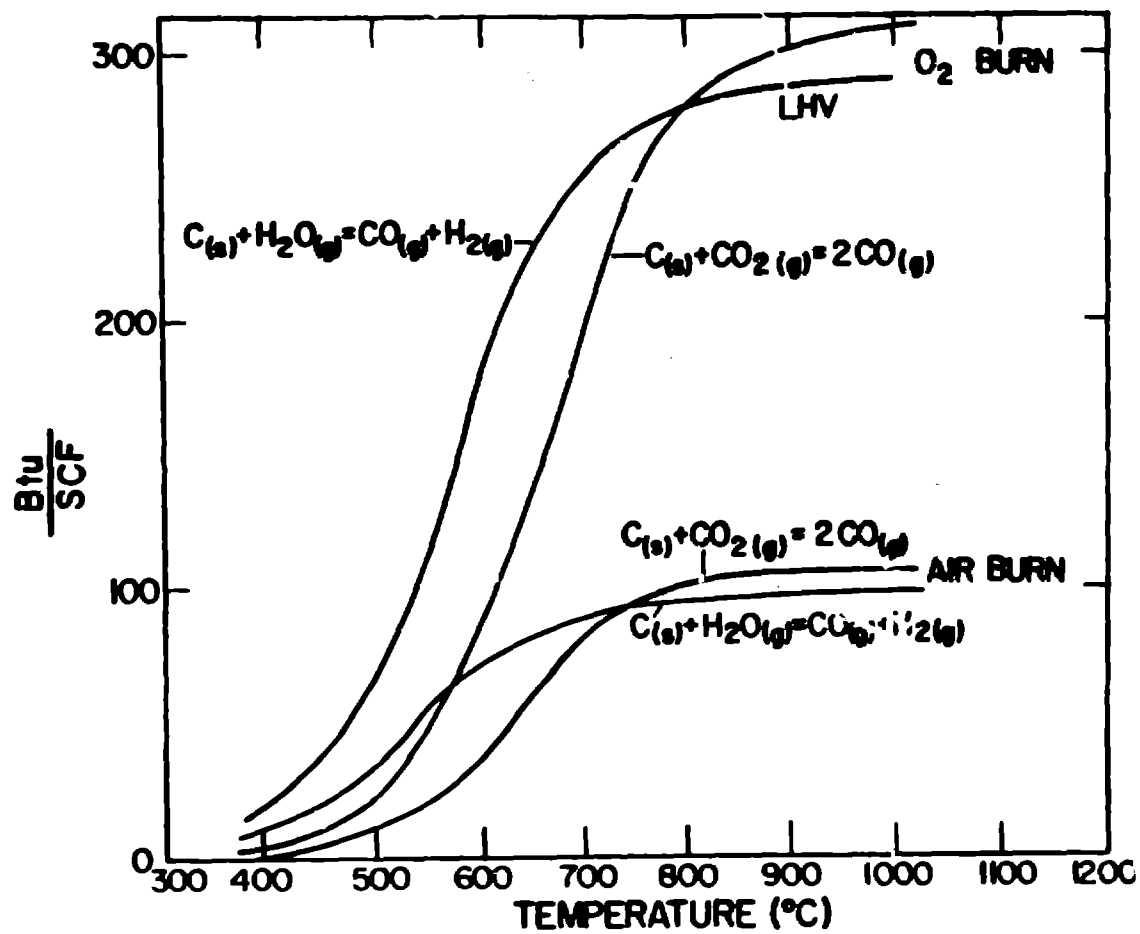


Fig. 1- Thermodynamic calculations of equilibrium fuel-gas production.